# PATENT APPLICATION

## METHOD AND APPARATUS FOR REACTING FLUIDS

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# METHOD AND APPARATUS FOR REACTING FLUIDS

## Background of the Invention

### 1. Field of the Invention

The present invention relates generally to bio-chemical reactor systems. More particularly, the present invention relates to a method and apparatus to generate a bio-chemical reaction in a micro total analysis system (μ-TAS).

### 2. Description of the Related Art

Reactions within a fluid or between fluids are at the heart of most systems that analyse bio-chemical processes. In macro engineering, mixing fluids and obtaining bio-chemical reactions are of great importance in the mining, food, petroleum, chemical, pharmaceutical, and industrial waste treatment industries. They are also important in micro engineering, especially, for micro total analysis system (μ-TAS) devices.

μ-TAS is loosely defined as a miniaturized device that includes and integrates all necessary parts and methods to perform a chemical analysis/synthesis. The system, which typically includes sample preparation, separation, and detection units, is formed within the confines of a single semiconductor chip. Examples of μ-TAS devices include microsensors, microactuators, and microfluidic devices. In microfluidic devices, research has always been focused on developing micropumps and valves to manipulate fluids inside a microfabricated structure.

The advantages of μ-TAS devices are closely associated with miniaturisation and integration of chemical and physical processes onto a semiconductor. One of the important goals in the development of μ-TAS devices is to shorten analysis and reaction times as well as to reduce the consumption of power, reagents, and samples. The use of μ-TAS devices also increases sample and product throughput resulting in higher yields and faster analysis when such systems are implemented in parallel.

The rate at which fluids achieve homogeneity in a μ-TAS device is crucial to achieving enhanced performance. Unfortunately, the rate of micromixing in μ-TASs limits overall system performance, particularly where the micromixing time is of the same order as or larger than the characteristic time constant of the reaction. In such cases, the reaction between the sample and reagent occurs simultaneously with the mixing of the two species. Consequently, the reactions between the two species may be suppressed as a result of insufficient mixing.

The term micromixing is generally used to describe fluid mixing at the molecular scale while microreacting refers to bio-chemical reactions at sub millimetre dimensions. Efficient micromixing and microreacting in μ-TAS devices is impeded by the small sizes of micromixers and microreactors, which prevent the forming of turbulent flow of the fluid. Because the microreactor operates on such a miniaturised scale, fluid flow within the microreactor is predominantly laminar. Therefore, micromixing is accomplished predominantly through the diffusion of molecules between adjacent fluid domains. This process of diffusion occurs as a result of random molecular motion along a concentration gradient and is a time consuming process.

In a laminar flow system characterised by a low Reynolds number of less than 30, the mixing time, $t$, that is, the time a molecule takes to diffuse over a diffusion distance, $x$, is expressed as follows:

$$t = \frac{\pi x^2}{4D} \qquad (1)$$

where $D$ represents the diffusion constant of the diffusing compounds. As evident from equation (1), the efficiency of a microreactor can be increased by minimising the diffusion distance $x$ to reduce the mixing time. To accelerate micromixing, the size of pure individual fluid elements is reduced until the scale of segregation reaches a sufficiently low level for the rate of molecular diffusion to become significant.

Distributive mixing, which involves the physical splitting of fluid streams into smaller segments and redistributing them so that the striation thickness of the laminate streams of the fluids is significantly reduced, is commonly employed to reduce mixing

time. Unfortunately, distributive mixing is not effective for fluids with low diffusion coefficients as the reduction in mixing time brought about by a reduction in the diffusive distance is insufficient to compensate for the increase in mixing time due to the low diffusion coefficient.

In view of the foregoing, it is desirable to have an apparatus and method for reacting fluids whose effectiveness is not limited to particular classes of fluids. It is also desirable to have an apparatus and method for reacting fluids that is not limited by small microreactor dimensions.

## Summary of the Invention

The present invention fills these needs by providing a method and apparatus for reacting fluids. It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system or a device. Several inventive embodiments of the present invention are described below.

In one embodiment of the present invention, a reactor is provided. The reactor comprises a chamber having an inlet and an outlet to receive and to output a fluid, respectively. A partition with a plurality of perforations is provided in the chamber to separate the fluid into fluid segments. A conductor coupled to the chamber generates a capacitance between the conductor and the partition to vibrate said partition.

Preferably, the partition and the conductor are coupled to a power source to generate a variable capacitance. Additionally, the conductor may be coupled to a support to prevent the conductor from vibrating. A heat exchange channel is preferably formed in the support to receive a flow of coolant to remove heat from the chamber. The partition and the conductor are preferably insulated to prevent an electrical disruption in the fluid and to the reactor, respectively.

In a preferred embodiment, the partition is configured to follow a vibrational pattern to prevent a back flow of the fluid. Preferably, the perforations have a diameter of about ten times a diameter of a molecule or cell in the fluid. More preferably, the inlet includes a plurality of openings to allow the fluid to enter the chamber in a plurality of layered streams. A sensor is preferably provided to measure a temperature of the fluid in the chamber or a pressure in the chamber.

In another embodiment of the present invention, a method of reacting a fluid is provided. The method begins by receiving the fluid in a chamber where the fluid is separated into a plurality of fluid segments and further vibrated to lower a diffusion distance of the fluid. Thereafter, the fluid is outputted from the chamber. The fluid is preferably separated into segments when the fluid flows through a partition having a plurality of perforations.

In a preferred embodiment, the fluid is vibrated by generating a capacitance between the partition and a conductor coupled to the chamber. Heat is preferably removed from the chamber by providing a heat exchange channel coupled to the chamber to receiving a flow of coolant.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

## Brief Description of the Drawings

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements.

Figure 1 illustrates a cross-sectional view of a reactor in accordance with one embodiment of the present invention.

Figure 2 illustrates a top view of a partition in accordance with one embodiment of the present invention.

Figure 3 illustrates a top view of a partition in accordance with one embodiment of the present invention.

Figure 4 illustrates a top view of a partition in accordance with one embodiment of the present invention.

Figure 5 illustrates a vibrational pattern of a partition in accordance with one embodiment of the present invention.

Figure 6a illustrates an enlarged side view of an inlet in accordance with one embodiment of the present invention.

Figure 6b illustrates an enlarged top view of an inlet in accordance with one embodiment of the present invention.

Figure 7 illustrates a top view of a heat exchange channel in accordance with one embodiment of the present invention.

Figure 8 illustrates a top view of a heat exchange channel in accordance with one embodiment of the present invention.

Figure 9 illustrates a method for reacting a fluid in accordance with one embodiment of the present invention.

## Detailed Description of the Preferred Embodiments

A method and apparatus for reacting fluids are provided. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be understood, however, to one skilled in the art, that the present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

Figure 1 illustrates a cross-sectional view of a reactor 10 in accordance with one embodiment of the present invention. Reactor 10 comprises a chamber 12 with an inlet 14 to receive a fluid and an outlet 16 to discharge the fluid. A partition 18 having a plurality of perforations 20 is provided inside chamber 12, while a plurality of conductors 22 is provided around chamber 12. Each of the plurality of conductors 22 and partition 18 are used to form an electric pole when powered by an alternating current source.

Partition 18 and conductors 22 are therefore coupled to a power source 24 to form a plurality of capacitors 26. Chamber 12 is provided with a support 28 coupled to conductors 22. Partition 18 is insulated to prevent a leakage of current into the fluid. Similarly, each conductor 22 is insulated from chamber 12, support 28, and one another to prevent a leakage of current into the fluid and an electrical disruption to reactor 10.

After entering chamber 12, the fluid flows through perforations 20 in partition 18. Perforations 20 are used to split and separate the fluid into smaller portions referred to as fluid segments. With reference to equation (1) above, segmentation of the fluid reduces diffusion distance $x$ between the fluid segments and therefore, reduces mixing time $t$. In addition when a current is applied to mixer 10, the capacitance between partition 18 and conductors 22 changes, generating an electrostatic force, which results in the vibration of partition 18. Conductors 22 do not vibrate as they are held rigidly in place by support 28. Accordingly, greater homogeneity is achieved in the fluid before the onset of the reaction, resulting in a shortened reaction time, as well as an increased sample and product throughput.

Segmentation of the fluid is also enhanced by the vibration of partition 18, which pushes the fluid inside chamber 12 to and away from partition 18. During the vibration, the fluid is broken down into even smaller fluid segments, which increases the interface between fluid segments. Diffusion between the fluid segments is again enhanced because of a further reduction in diffusion distance. Simulation studies have shown that the vibration of partition 18 enhances the mixing of the fluid to such an extent that reactor 10 is effective for fluids with very small diffusion constants, *i.e.* less than $10^{-10}$ $m^2/s$.

Figure 2 illustrates a top view of partition 18 in accordance with one embodiment of the present invention. Partition 18 sections chamber 12 into an upper chamber 12a and a lower chamber 12b. An insulator 30 may be provided to segment partition 18 into a plurality of sections according to the number of capacitors 26 to be formed. For example, in this embodiment, chamber 12 is provided with four conductors: a pair of conductors on either side of partition 18, to form four capacitors with partition 18. Accordingly, insulator 30 is provided to segment partition 18 into a first section 18a and a second section 18b.

The shape, size, and arrangement of each perforation 20 may be altered to suit the characteristics of the fluid. For example, a fluid with large molecules or cells will require larger perforations than one with small molecules or cells. Preferably, the diameters of perforations 20 are about ten times the diameter of the fluid molecules or cells of biological matter. Partition 18 is also preferably narrower than chamber 12 to prevent friction with the walls of chamber 12 during vibration.

Figure 3 illustrates a top view of a partition 18' in accordance with one embodiment of the present invention. In this embodiment, partition 18' includes a plurality of perforations 20', which are rectangular in shape. Figure 4 illustrates a top view of a partition 18" in accordance with one embodiment of the present invention. In this embodiment, partition 18" includes a plurality of perforations 20", which are elliptical in shape. Perforations of different sizes and shapes as illustrated in Figures 3 and 4 may be configured to accommodate all manner of varying dimensions of molecules and cells that may be used in reactor 10. For example, the use of perforations 20", may be preferred for liquids with long molecules or disk shaped cells.

The power required to vibrate partition 18 is inversely proportional to the size of perforations 20 if the efficiency of mixing is held constant. A fluid passing through small perforations instead of large perforations will require greater power to cause the same magnitude of diffusion. Therefore, a higher voltage is required when smaller perforations are used. The applied voltage used in reactor 10 is preferably about or less than 5 Volts for most applications.

The vibration of partition 18 is preferably configured to follow vibrational patterns that reduce the amount of back flow of the fluid into inlet 14. The vibrational patterns of the partition are thus designed to keep the effective volume of the upper and lower chambers 12a and 12b constant. This in turn increases the probability that fluid will only circulate between the two partitioned chambers and reduces the probability of back flow into inlet 14.

An example of a vibrational pattern 32 (modelled after a cosine curve) for partition 18 is illustrated in Figure 5 in accordance with one embodiment of the present invention. First half 34 of vibrational pattern 32, corresponding to first section 18a of partition 18, vibrates 180° out-of-phase with a second half 36, corresponding to second section 18b, to ensure that an effective volume of upper chamber 12a and lower chamber 12b remains substantially unchanged while partition 18 vibrates. Hence, no back flow is generated as partition 18 vibrates.

An enlarged view of inlet 14 is illustrated in Figures 6a and 6b. Figure 6a illustrates an enlarged side view of inlet 14 in accordance with one embodiment of the present invention. Inlet 14 comprises a two-way junction with a first opening 38 and a second opening 40. Figure 6b illustrates an enlarged top view of inlet 14 in accordance with one embodiment of the present invention. First opening 38 and second opening 40 are configured to allow the fluid to enter chamber 12 in layered streams. Inlet 14 may be modified to include additional openings to provide additional layered streams.

Referring back to Figure 1, support 28 may be provided with a heat exchange channel 42. A coolant flows through heat exchange channel 42 to remove a heat of reaction from chamber 12. Examples of heat exchange channel 42 are illustrated with reference to Figures 7 and 8.

Figure 7 illustrates a top view of heat exchange channel 42 in accordance with one embodiment of the present invention. Heat exchange channel 42 comprises an inlet channel 44 to receive a coolant and an outlet channel 46 to discharge the coolant. Inlet channel 44 is coupled to outlet channel 46 by a plurality of intermediate channels 48, which are preferably arranged perpendicular to inlet channel 44 and outlet channel 46. The coolant is sequentially distributed into intermediate channels 48 as the coolant flows through inlet channel 44, and subsequently combined through sequential introduction into outlet channel 46. Heat from chamber 12 is removed as the coolant flows through heat exchange channel 42.

An alternative embodiment of heat exchange channel 42 is illustrated in Figure 8. Heat exchange channel 42 comprises an inlet channel 50 to receive a coolant and an outlet channel 52 to discharge the coolant. Inlet channel 50 is coupled to a plurality of intermediate channels 54, which is coupled to form outlet channel 52. A uniform distribution of the coolant is achieved with this arrangement of inlet channel 50, outlet channel 52, and intermediate channels 54. Correspondingly, a uniform temperature distribution is realized in chamber 12.

With reference to Figure 1, a plurality of sensors 56 is provided in support 28. Sensors 56 are used to measure a temperature of the fluid in chamber 12 and/or a pressure in chamber 12. A control system (not illustrated) is also used to adjust a flow rate of the fluid into and out of chamber 12, as well as a flow rate of the coolant, based on the temperature and the pressure measured by sensors 56 to maintain a desired process environment in chamber 12.

Figure 9 illustrates a method 100 for reacting a fluid in accordance with one embodiment of the present invention. Method 100 begins at a block 102 when a fluid is received in a chamber of a reactor. While in the chamber, the fluid is separated in a block 104 into a plurality of fluid segments. The separation occurs when the fluid is forced to flow through a partition having a plurality of perforations. Separation of the fluid into fluid segments enhances mixing by lowering the diffusion distance between molecules in the fluid.

At the same time the fluid is being segmented in the present invention, the fluid is vibrated while it is in the mixing chamber in a block 106. The mixing is accomplished by utilizing a plurality of conductors coupled to the mixing chamber. The conductors and the partition are coupled to a power source to generate a capacitance between the conductors and the partition. The capacitance then causes the partition to vibrate to enhance fluid mixing. The conductors do not vibrate as they are held rigidly in place by a support for the chamber. Finally, the fluid is outputted from the chamber in a block 108.

Any heat generated by the bio-chemical reaction in the chamber may be removed in a block 110 from the fluid in the chamber by the flow of a coolant through a heat exchange channel in the support. Additionally, a flow rate of the fluid into and out of the chamber, as well as a flow rate of the coolant, may be adjusted in a block 112 to maintain a desired process condition in chamber 12.

An advantage of the present invention is that the microreactor is effective for mixing a wide variety of fluids in a very small mixing environment, particularly fluids with lower diffusion coefficients. By using a partition to split and separate the fluids into fluid segments, the present invention overcomes low diffusion coefficients by reducing the diffusion distance between the fluids to be mixed. The design of the microreactor inlets of the present invention also shortens reaction time and increases sample and product throughput by receiving the fluid in layered streams.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. The embodiments and preferred features described above should be considered exemplary, with the invention being defined by the appended claims.